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A.P. Fairall and P.A. Woudt

The Current Status of Primary Distance Indicators

Michael Feast

Astronomy Dept, University of Cape Town, Rondebosch, 7701, South Africa
mwf@artemisia.ast.uct.ac.za

Abstract. A review is given of the current status of the primary distance indicators. The relevance of these indicators for determining the local expansion rate and the age of globular clusters is briefly outlined.

1. Introduction

In the cosmological context, primary distance indicators are of importance as the calibrators of those more general indicators that determine the local expansion rate and deviations from it. They are also of importance in estimating the ages of globular clusters and hence a lower limit to the age of the Universe. This talk has the quite limited objective of giving an overview of the current calibration of primary distance indicators, and particularly trying to draw attention to present uncertainties. Some implications of this work will then be briefly discussed.

2. Cepheids

The best known primary distance indicators are of course the Cepheids. The slope of the Period-Luminosity Relation in the V band, $PL(V)$, has generally been taken from the LMC Cepheids. However the zero-point, and hence the scale, can be set by observations in our own Galaxy. Table 1 lists four ways of doing this Galactic calibration and gives the corresponding zero-points, γ , of the $PL(V)$ relation;

$$M_V = -2.81 \log P + \gamma \quad (1)$$

The straight forward and fundamental way is to use trigonometrical parallaxes of nearby Cepheids. The value in the Table 1 combines Hipparcos parallax results (Feast & Catchpole 1997) with a parallax of delta Cephei itself obtained by Benedict et al. using the HST (see Benedict et al. 2002b, Feast 2002). A group led by Fritz Benedict has an HST project in progress to determine the parallaxes of 10 other local Cepheids. It is hoped that the relative parallax errors of the 10 stars, which is 35 percent in Hipparcos will be reduced to about 8 percent. The stars cover a range in period and so should give us some hold on the $PL(V)$ slope in our Galaxy.

Before the Hipparcos improvements of Cepheid parallaxes, the most favoured way of fixing the Cepheid scale was from Cepheids in open clusters, using distances from main sequence fitting. This method has a number of problems. For

Table 1.

The Cepheid Zero-point		
Method	γ	Δ
Trig. Parallax	-1.36 ± 0.08	-0.01
Stat. Parallax	-1.46 ± 0.13	-0.11
Puls. Parallax	$-1.31 \pm (0.04)$	+0.04
Clusters	$-1.45 \pm (0.05)$	-0.10
Unweighted (4)	-1.40	
NGC4258	-1.17 ± 0.13	+0.18
Unweighted (5)	$-1.35 \pm (0.05)$	

instance the steepness of the main sequence makes the method sensitive to the adopted reddening and also to photometric errors. The standard method has been to use the Pleiades as a template with some adopted Pleiades modulus. Although the individual Hipparcos parallaxes of Pleiades stars are relatively poor due to its considerable distance, van Leeuwen (1999, 2000) and Robichon et al. (2000) obtained a mean parallax of good internal consistency by combining all the Hipparcos results for stars in the cluster. The distance derived was considerably smaller than expectations. In view of doubts regarding these results it has seemed prudent to use as a standard the distance of the Hyades which is much closer and for which good Hipparcos parallaxes of individual stars were obtained (Perryman et al. 1998). It is a simple matter to derive from main sequence fits the relative Hyades/Pleiades distances. It does however require a correction for the Hyades metallicity, though this is believed to be well known and this leads to the cluster result in Table 1 (Feast 2000, 2003).

It is worth discussing briefly the “Pleiades problem” and to see what its implications are for Hipparcos parallaxes in general. Makarov (2002, 2003) has investigated this problem in some detail. These papers suggest that the Hipparcos reference frame suffers from slight random errors which, in a small area of the sky, may be correlated to some extent. The uncertainty of the mean parallax of N stars in such an area may then not decrease as $\text{root } N$. By going back to the original Hipparcos data Makarov shows how this problem can be at least partially overcome. Makarov’s result leads to the Pleiades modulus given in Table 2.

Whilst a problem of this kind may be important for some clusters, Makarov’s work suggests that for objects scattered over the sky this type of error will be randomly distributed and the individual parallaxes of such objects can be combined satisfactorily in the normal way. Whether further work will establish that the overall standard errors of Hipparcos stars need to be slightly increase is not yet clear. Even if they did, the method of reduced parallaxes which is used for instance in reducing the Cepheid data (e.g. Feast & Catchpole 1997), only relies on the relative values of the absolute errors of the stars involved and since these

Table 2.

The Pleiades Modulus		
Method	Modulus	Δ
Original Hipparcos	5.37 ± 0.07	
Revised Hipparcos	5.57 ± 0.06	-0.05
Atlas	5.67 ± 0.04	+0.05
HD 23642	5.60 ± 0.04	-0.02
Via Hyades	5.66	+0.04
Unweighted (4)	5.62	

vary little from star to star the effect seems likely to be small, though of course it would be desirable to have numerical confirmation of this.

Besides the revised Hipparcos modulus of the Pleiades, Table 2 contains two other recent estimates. Pan et al.(2004) obtain a distance from an interferometric orbit of the binary member, Atlas, together with an adopted mass-luminosity relation. Another estimate is found from the eclipsing binary member, HD23642 (Munari et al. 2004), adopting a colour-surface brightness relation. Table 2 shows that all the current values, including the result obtained via the Hyades, which has been adopted in the present discussion, agree well (Δ is the residual from the final mean).

There are two other methods of fixing the galactic Cepheid scale shown in Table 1; statistical parallaxes and pulsation parallaxes. The main uncertainty in the case of statistical parallaxes is the need to adopt a model of galactic motions. Fortunately in the case of the Cepheids distributed over a large volume, their motions are dominated by differential galactic rotation. This is independently demonstrated by both proper motions and radial velocities. The radial velocity data can then be easily scaled to fit the proper motion results and to yield the scale. The zero-point quoted uses Hipparcos proper motions and is from Feast & Whitelock (1997). There has been extensive further work on stellar proper motions generally, for instance the current US Naval Observatory catalogue (Zacharias et al. 2004), and it would be worthwhile investigating whether they contain data which could be used to improve the zero-point.

There is much work at present on various forms of the pulsation parallax method. These include the current ability to determine the angular diameters of Cepheids, and their variation with phase, using interferometry (see for instance, Fouque, Storm & Gieren 2003 and references there, also Kervella et al. 2003, 2004a,b). Pulsation parallaxes can give results of high internal consistency. However it is quite difficult to estimate possible systematic uncertainties in combining radial velocities with surface brightness or angular diameter measures, due to limb darkening, atmospheric complexities etc. (see for instance, Marengo et al. 2003a,b). The value adopted here is from Laney (1998) as representative

I have included in Table 1 the zero-point derived using Cepheids in NGC4258 whose distance is derived from the motions of H₂O masers round a central black

hole – together with a model (Herrnstein et al. 1999, Newman et al. 2001). The metallicity of this galaxy is close to solar, so only a small metallicity correction was required. The deviation from the mean (Δ) is not significant.

A good deal of the current effort on Cepheids is being put into investigating in detail whether the PL relation is exactly linear and how its slope and zero-point are affected by metallicity (e.g. Gieren et al. 1998, Tammann et al. 2003, Sandage et al. 2004, Kennicutt et al. 1998, Groenewegen et al. 2004, Storm et al. 2004, Sakai et al. 2004). The slope has in the past been taken from the metal-poor LMC Cepheids. Both pulsation parallaxes and Cepheids in clusters suggest that for galactic Cepheids the slope in PL(V) is slightly different. This is important because the weighted mean abundance of the HST key project galaxies is near solar. Thus for instance using the galactic slope of Gieren et al (1998) from pulsation parallaxes, rather than the LMC slope, together with the trigonometrical parallaxes would lead to an increase in the HST key project distance scale of about 7 percent and a corresponding decrease in H_0 , due to the difference in mean period of the calibrating and programme Cepheids. This gives some idea of the current uncertainties.

3. The RR Lyrae Variables

Table 3 lists estimates of the zero-point (ρ) of the RR Lyrae, absolute magnitude - metallicity relation;

$$M_V = 0.2([Fe/H] + 1.5) + \rho \quad (2)$$

The adopted slope is a compromise between various suggested values (see e.g. Gratton et al. 2003).

Table 3.

The RR Lyrae Zero-point		
Method	ρ	Δ
Trig. Par.	0.57 ± 0.11	0.00
Hor. Branch	0.56 ± 0.15	-0.01
Globulars	0.56 ± 0.07	-0.01
δ Sct	0.44 ± 0.10	-0.13
Stat. Par.	0.74 ± 0.13	+0.17
Unweighted (5)	0.57	

The parallax result (Feast 2002) is from the HST parallax of RR Lyrae itself determined by Benedict et al. (2002a). In principle the HST could be used to obtain parallaxes of other RR Lyraes which would substantially improve this estimate. The statistical parallax result (Gould & Popowski 1998) is based on a simple model of galactic halo kinematics which is questionable in view of the possible effects of streams. The other entries in Table 3 are from horizontal branch stars with Hipparcos parallaxes (Gratton 1998), from globular clusters with distances from Hipparcos subdwarfs (Gratton et al. 2003), and via the Hipparcos parallaxes of δ Sct stars (McNamara 1997). An unweighted mean of all the estimates is given in Table 3.

4. The Mira Variables

The infrared (K) PL relation for Miras was established in the LMC. It has a small scatter (Feast et al. 1989) and avoids the reddening problem which is significant in the optical region.

An initial calibration of this relation using Hipparcos parallaxes (Whitelock & Feast 2000) has recently been revised by Whitelock (to be published) taking into account the chromatic corrections to the parallaxes that have been suggested (Knapp et al. 20003, Platais et al. 2003 Pourbaix et al. 2003). Both the original and revised result are shown in the Table 4 (note that the small bias corrections discussed in Feast (2002) have been applied).

Table 4. The Mira PL(K) Zero-point

Method	κ	Δ
Original Hipparcos Par.	0.86 ± 0.14	
Revised Hipparcos Par.	1.06 ± 0.13	$+0.06$
OH VLBI	1.01 ± 0.13	$+0.01$
Globular Clusters	0.93 ± 0.14	-0.07
Unweighted (3)	1.00 ± 0.08	

Also in Table 4 are the zero-point derived using the distances of a few Miras obtained from VLBI of their OH masers (Vlemmings et al. 2003) and via metal-rich globular clusters which contain Miras and have Hipparcos sub-dwarf distances (Feast et al. 2002). The agreement between the various methods (Δ in Table 4) is better than one could reasonably expect.

The power of this method of distance determination was recently demonstrated by Rejkuba (2004) who used the K magnitudes and periods of about 1000 Miras in NGC5128 (Cen A) to obtain a distance for this galaxy. Her results indicate that the PL(K) slope is closely the same in the LMC and in NGC5128 and that based on the LMC distance modulus adopted below (Table 5), the Mira modulus (28.0 ± 0.2) agrees with that found from the RGB tip (27.9 ± 0.2) ¹.

5. Intercomparison of Primary Distance Indicators

It has often been suggested that the distance of the LMC is of fundamental importance in the distance scale problem. However the basic zero-points are best established in Our Galaxy. Nevertheless the LMC is of importance for comparing distance indicators with one another.

Table 5 lists LMC distance moduli derived using various distance indicators. The Cepheid modulus uses the mean zero-point of Table 1 together with a

¹A discussion of the RGB tip is not given here since although it seems a good distance indicator its calibration depends either on other (primary) distance indicators or theory.

Table 5.

LMC Modulus	
Method	Modulus
Cepheids	18.52
RR Lyraes	18.49
Miras	18.48
Eclipsers	18.40:
Red Clump	18.52
SN1987A	18.58
Unweighted(6)	18.50

metallicity correction (see Feast 2003 for details). The Mira modulus uses the mean result of Table 4 together with the data of Feast et al. (1989). The RR Lyrae modulus uses the zero-point of Table 3 together with the LMC data of Clementini et al. (2003). The result for eclipsing variables is from Ribas et al. (2002). The considerable spread in moduli of the binaries studied is worrying (see Ribas et al. and Feast 2003). The red clump modulus depends on absolute magnitudes derived from Hipparcos parallaxes of galactic clump stars. These require correction for both age and metallicity effects and the quoted result depends on Girardi and Salaris (2001) and Alves et al. (2002). The result from the ring round SN1987A is from Panagia (1998).

A low value of the LMC Modulus (18.35 ± 0.05) has been suggested from main sequence fitting to the young cluster NGC 1866 (Walker et al. 2002). I have not included this since there are uncertainties affecting the photometric calibration and reddening, and the need for a large metallicity correction (see Feast 2003, Salaris et al. 2003, Groenewegen & Salaris 2003).

6. Basic Distance Indicators and Cosmology

Eight years ago when the Hipparcos parallaxes were released, they indicated a zero-point for metal-normal Cepheids about 8 percent (0.17 mag) brighter than that then being used by the HST Key project group (Feast & Catchpole 1997, Feast 1998). This difference has now been virtually eliminated by two effects. The mean galactic zero-point in Table 1 is 0.08 mag fainter than the 1997 parallax value, whilst the key project team (Freedman et al. 2001) now apply a metallicity correct to their LMC Cepheids which effectively increases their scale by 0.08 mag.

Whilst this basic agreement is heartening, it is important to bear two things in mind.

(1) When one is trying to calibrate zero-points of Cepheids (or anything else) at the 0.1mag level, all sorts of problems, some of which have been mentioned above, arise. These are currently being studied by a number of workers and one cannot realistically claim that they have all been solved.

(2) Whist we are getting agreement on the basic scale there remain significant differences in the values of H_0 derived by the Key programme group (Freedman et al. 2001) who find $71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (from SNIa) and the SNIa

group (e.g. Tammann et al. 2002) who find $60 \text{ km s}^{-1} \text{ Mpc}^{-1}$. using effectively the same basic calibration. These differences arise to some extent in the interpretation of HST data and may not be entirely solved till there are more and better observations from space.

One may reasonably ask why one should want to improve on the Cepheid based value of H_0 . Don't we get a more accurate value from a combination of WMAP with other surveys (e.g. 2dF)(Spergel et al. 2003, Lahav, this volume) and a Λ CDM model? However the Λ CDM model is of such significance that it would seem expedient to test it to the best of our ability, and one way to do this is to derive an independent value of H_0 .

Another way to confront results from large scale structure is from estimates of the age of the Universe, for which globular clusters give us a lower limit. This too is partly a distance scale problem. A change in distance modulus of 0.1 mag results in a change of age of about 1 Gyr. At present the best ages are from main-sequence turn-offs with distance from main-sequence fitting of subdwarfs. The evidence suggests that the most metal-poor clusters are the oldest. This introduces a problem since there are hardly any subdwarfs with suitable parallaxes that are as metal-poor as the most metal-poor globular clusters. The best distance estimate for a metal-poor cluster is probably that of NGC 6397 by Gratton et al. (2003). They find the values listed in Table 6 without and with diffusion. For an estimate of the age of the universe we have to add the epoch of cluster formation. If cluster formation is dated to around $z = 10$ then we must add 0.5 Gyr. Very recently two papers have discussed the effects on stellar models from a revision of the important $^{14}\text{N}(\text{p}, \gamma)^{15}\text{O}$ rate (Imbriani et al. 2004, Degl'Innocenti et al. 2003). This work indicated that globular cluster ages need increasing by between 0.7 and 1.0 Gyr. If we adopt 0.8 Gyr for this correction, the final result for the age of the Universe is 14.8 Gyr for a model including diffusion, compared with 13.7 ± 0.2 Gyr from a combination of WMAP, 2dF etc. In view of the uncertainties in the globular cluster age there is no evidence for disagreement but it whets ones appetite for better cluster ages. Whilst it is rather difficult to be sure of the uncertainties in stellar evolutionary theory, much of the presently adopted estimates of uncertainties in globular cluster ages lies in the uncertainties in their derived distances. Clearly work to improve these would be very valuable.

Table 6. The Globular Cluster NGC 6397

	Age (Gyr)
No Diffusion	13.9 ± 1.1
With Diffusion	13.5 ± 1.1
$^{14}\text{N}(\text{p}, \gamma)^{15}\text{O}$ Correction	0.8
Corrected Age	14.3 or 14.8
$z = 10$ Correction	0.5
Estimated Age of Universe (NGC 6397)	$14.8 \text{ or } 15.2 \pm \geq 1.1$
Estimated Age of Universe (WMAP)	13.4 ± 0.3
Estimated Age of Universe (WMAP/2dF etc.)	13.7 ± 0.2

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